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On the condition numbers of a multiple generalized eigenvalue

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Abstract For standard eigenvalue problems, a closed-form expression for the condition numbers of a multiple eigenvalue is known. In particular, they are uniformly 1 in the Hermitian case, and generally take different values in the non-Hermitian case. We consider the generalized eigenvalue problem and identify the condition numbers of a multiple eigenvalue. Our main result is that a multiple eigenvalue generally has multiple condition numbers, even in the Hermitian definite case. The condition numbers are characterized in terms of the singular values of the outer product of the corresponding left and right eigenvectors.

Keywords multiple eigenvalue · generalized eigenvalue problem · condition number

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1 Introduction

This paper is concerned with the sensitivities of a multiple eigenvalue in generalized eigenvalue problems $Ax = \lambda Bx$. When perturbations are introduced in the matrices, a multiple eigenvalue λ_0 of multiplicity r generally splits into r simple eigenvalues. We are interested in how sensitively each of the r eigenvalues can be perturbed.

The first order perturbation expansion for a simple eigenvalue is a well-known result [9,10], and that for a multiple eigenvalue is also studied in [12] for standard eigenvalue problems, and in [1] for generalized eigenvalue problems, including singular matrix pairs. Using such results and following the

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definition of r condition numbers of a multiple eigenvalue for standard eigenvalue problems introduced in [13], we naturally define condition numbers for the generalized case, as shown below in (4).

Sun shows in [13] that the r condition numbers $\kappa_i(A, \lambda_0)$ for $i = 1, \dots, r$ of a nondefective multiple eigenvalue of a non-Hermitian matrix are expressed by

$$\kappa_i(A, \lambda_0) = \left(\prod_{j=1}^i c_j(A, \lambda_0) \right)^{1/i} \quad \text{for } i = 1, \dots, r, \quad (1)$$

where $c_j(A, \lambda_0)$ are the secants of the canonical angles between the left and right invariant subspaces corresponding to the multiple eigenvalue. When A is non-Hermitian $c_i(A, \lambda_0)$ generally take different values for different i , hence so do $\kappa_i(A, \lambda_0)$ and (1) shows that a multiple eigenvalue has multiple condition numbers. Contrarily, in the Hermitian case we have $c_j(A, \lambda_0) \equiv 1$, so $\kappa_i(A, \lambda_0) = 1$ for $i = 1, \dots, r$. Hence (1) also shows the well-known fact that a multiple eigenvalue of a Hermitian matrix always has a uniform condition number 1.

Since a standard non-Hermitian eigenvalue problem can be regarded as a special case of the generalized non-Hermitian eigenvalue problem $Ax = \lambda Bx$, it is clear that a multiple eigenvalue in this case must have multiple condition numbers. On the other hand, in the important case of the generalized Hermitian definite pair (where A and B are Hermitian and B is positive definite), it is not trivial whether or not the condition numbers $\kappa_i(A, B, \lambda_0)$ for $i = 1, \dots, r$ take different values. In this paper we identify their expression, which shows that they generally do take r different values. We shall see that there are two sources for this different conditioning, namely the difference between the left and right eigenvectors (as present in non-Hermitian standard eigenproblems), and the fact that the B -orthonormal eigenvectors have different 2-norms (as present in the case $B \neq I$).

It is important to note that in the Hermitian definite case, a natural choice of metric can be based on the B -based inner product $(x, y)_B = x^H B y$ instead of the standard inner product $(x, y) = x^H y$. This leads to the standard eigenvalue problem for the Hermitian matrix $B^{-1/2} A B^{-1/2}$, so in this inner product all the condition numbers are the same (see the second remark in section 3.2). Our discussion in this paper assumes the use of the standard inner product.

The condition numbers κ_i for $i = 1, \dots, r$ of a nondefective finite multiple eigenvalue in four situations are summarized in Table 1, expressed in terms of $\sigma_1, \dots, \sigma_r$, the r positive singular values of $X_1 Y_1^H$ (see section 2.1). The contribution of this paper is that we fill in the second row, that is, we identify the condition numbers of a multiple eigenvalue in a generalized eigenvalue problem, both for the Hermitian definite case and the non-Hermitian case. Here τ is a prescribed positive constant that accounts for perturbation scalings, see section 2.1.

There are a number of related studies in the literature. [4] investigates the Hölder condition number, which is essentially κ_1 in our terminology when λ_0 is

Table 1 Summary of condition numbers κ_i of a multiple eigenvalue for $i = 1, \dots, r$.

	Hermitian	Non-Hermitian
$Ax = \lambda x$	1	$\left(\prod_{j=1}^i \sigma_j\right)^{1/i}$
$Ax = \lambda Bx$	$(1 + \tau \lambda_0) \min_{1 \leq j \leq i} \sqrt{\sigma_j \sigma_{i-j+1}}$	$(1 + \tau \lambda_0) \left(\prod_{j=1}^i \sigma_j\right)^{1/i}$

nondefective. The focus of [4] is the effect of the structure of the perturbation on the Hölder condition number, and in section 4.1 we discuss how our results are related to those in [4].

An observation that a multiple generalized eigenvalue has different sensitivities under perturbations was first made in [10, p.300], which mentions that a multiple eigenvalue of a pair such as $A = \begin{bmatrix} 2000 & 0 \\ 0 & 2 \end{bmatrix}$, $B = \begin{bmatrix} 1000 & 0 \\ 0 & 1 \end{bmatrix}$ tends to behave differently under perturbations in A and B . We note that as shown in [14], for Hermitian definite pairs, small componentwise relative changes in A and B can introduce only small relative perturbation to any eigenvalue, and it is easy to see the two eigenvalues of the above pair (A, B) have similar perturbation behaviors. However, in terms of “standard” normwise perturbation, that is, when (A, B) is perturbed to $(A + \epsilon E, B + \epsilon F)$ under $\|E\|_2, \|F\|_2 \leq 1$ and $\epsilon \rightarrow 0$, a multiple eigenvalue can exhibit different behaviors. [7, 5] consider the Hermitian definite case and give an explanation for this behavior, presenting r different perturbation bounds for λ_0 under perturbations of finite norm. The approach of this paper is different in that our focus is on the condition numbers, which are attainable perturbation bounds in the first order sense in the limit $E, F \rightarrow 0$. The bounds in [7, 5] are valid for non-asymptotic E, F but are less tight (generally not attainable) when $E, F \rightarrow 0$.

Our arguments closely follow that of [13], in which the condition numbers are called *worst-case* condition numbers, to emphasize the difference from the *typical-case* condition numbers, as presented in [11]. In this sense, our results should also be regarded as worst-case condition numbers, in that κ_i are the largest attainable bounds in the first order sense. Experiments show that these bounds are not likely to be attained in practice for randomly generated perturbations, especially for large i (see the example in section 4.1).

The structure of this paper is as follows. First in section 2 we establish a characterization of condition numbers of a multiple generalized eigenvalue. In section 3 we treat the Hermitian definite case and show that a multiple generalized eigenvalue indeed has multiple condition numbers. Section 4 treats the general non-Hermitian case, in which we give simple numerical examples to illustrate our results. We also discuss the case of an infinite and defective multiple eigenvalue.

Notations: $\sigma_i(X)$ denotes the i th largest singular value of a rectangular matrix X . $\lambda_i(A)$ denotes the i th eigenvalue of A , arranged in decreasing order of magnitude. We use only the matrix spectral norm $\|\cdot\|_2$, so that $\|A\|_2 =$

$\sigma_1(A)$. We use MATLAB notation, in which $V(i, j : k)$ denotes the j th to k th elements of the i th row of V . I_k is the identity matrix of order k .

2 Condition numbers of a multiple generalized eigenvalue

2.1 Definition

For an n -by- n matrix pair (A, B) , suppose that λ_0 is a nondefective finite multiple eigenvalue (we discuss the infinite and defective cases later in section 4.3) of multiplicity r , so that there exist nonsingular matrices $X = (X_1, X_2)$ and $Y = (Y_1, Y_2)$ with $X_1, Y_1 \in \mathbb{C}^{n \times r}$ that satisfy

$$Y^H AX = \begin{bmatrix} \lambda_0 I_r & 0 \\ 0 & J_A \end{bmatrix}, \quad Y^H BX = \begin{bmatrix} I_r & 0 \\ 0 & J_B \end{bmatrix}. \quad (2)$$

Here the spectrum of the pair (J_A, J_B) does not contain λ_0 . Then, the pencil $(A + \epsilon E, B + \epsilon F)$ has eigenvalues $\hat{\lambda}_1, \hat{\lambda}_2, \dots, \hat{\lambda}_r$ admitting the first order expansion [6,4]

$$\hat{\lambda}_i = \lambda_0 + \lambda_i(Y_1^H(E - \lambda_0 F)X_1)\epsilon + o(\epsilon), \quad i = 1, 2, \dots, r, \quad (3)$$

where $\lambda_i(Y_1^H(E - \lambda_0 F)X_1)$ are the eigenvalues of $Y_1^H(E - \lambda_0 F)X_1$ for $i = 1, \dots, r$. In light of (3) and following the definition presented in [13], we define r condition numbers $\kappa_i(A, B, \lambda_0)$ for $i = 1, \dots, r$ of the multiple eigenvalue λ_0 as follows.

Definition 1 Let an n -by- n matrix pair (A, B) have the decomposition (2), and let $\tau > 0$ be a prescribed constant. We define the condition numbers of λ_0 , a multiple eigenvalue of (A, B) of multiplicity r , by

$$\kappa_i(A, B, \lambda_0) \equiv \sup_{\|E\|_2 \leq 1, \|F\|_2 \leq \tau} |\lambda_i(Y_1^H(E - \lambda_0 F)X_1)|, \quad i = 1, \dots, r, \quad (4)$$

where the eigenvalues $\lambda_i(Y_1^H(E - \lambda_0 F)X_1)$ are ordered such that $|\lambda_1(Y_1^H(E - \lambda_0 F)X_1)| \geq |\lambda_2(Y_1^H(E - \lambda_0 F)X_1)| \geq \dots \geq |\lambda_r(Y_1^H(E - \lambda_0 F)X_1)|$.

In words, $\kappa_i(A, B, \lambda_0)$ measures by how much small changes in A and B can be magnified in the multiple eigenvalue λ_0 , in the first order sense. τ is a positive constant that allows for the case where perturbations in A and B occur in different magnitudes, which is a notion adopted for example in [3].

2.2 Equivalent characterization of $\kappa_i(A, B, \lambda_0)$

Here we show that $\kappa_i(A, B, \lambda_0)$ can be expressed in an equivalent form, just as in the standard ($B = I_n$) case $\kappa_i(A, \lambda_0)$ can be expressed as (1) using the secants of the canonical angles $c_j(A, \lambda_0)$ between the left and right invariant subspaces corresponding to λ_0 . Note that $c_j(A, \lambda_0) = \sigma_j(X_1 Y_1^H)$ for $j = 1, \dots, r$.

In this paper we use the quantity $\sigma_j(X_1 Y_1^H)$ instead of the canonical angles to identify the condition numbers, because it allows us to treat generalized eigenvalue problems in a uniform way.

We use the proof of Theorem 2.1 in [13], whose crucial identity is

$$\begin{aligned} |\lambda_i(Y_1^H(E - \lambda_0 F)X_1)| &= |\lambda_i((E - \lambda_0 F)X_1 Y_1^H)| = |\lambda_i((E - \lambda_0 F)U\Sigma V^H)| \\ &= |\lambda_i(V^H(E - \lambda_0 F)U\Sigma)| \end{aligned}$$

for $i = 1, \dots, r$, where $X_1 Y_1^H = U\Sigma V^H$ is the “thin” SVD. Here, to get the first and last equalities we used the fact [10, p.27] that for general $X \in \mathbb{C}^{n \times m}$ and $Y \in \mathbb{C}^{m \times n}$, the nonzero eigenvalues of XY and those of YX are the same. Since V and U have orthonormal columns and E, F can take arbitrary matrices with $\|E\|_2 \leq 1, \|F\|_2 \leq \tau$, it follows that $V^H E U, V^H F U$ can also take arbitrary matrices such that $\|V^H E U\|_2 \leq 1, \|V^H F U\|_2 \leq \tau$. Hence, redefining $E := V^H E U$ and $F := V^H F U$, we see that the condition numbers $\kappa_i(A, B, \lambda_0)$ have the following equivalent characterization.

Lemma 1 *Under the assumptions in Definition 1, suppose that $X_1 Y_1^H = U\Sigma V^H$ is the SVD where $\Sigma = \text{diag}(\sigma_i)$ is r -by- r ($\sigma_1 \geq \sigma_2 \geq \dots \geq \sigma_r > 0$). Then, $\kappa_i(A, B, \lambda_0)$ in (4) can be expressed as*

$$\kappa_i(A, B, \lambda_0) \equiv \sup_{\|E\|_2 \leq 1, \|F\|_2 \leq \tau} |\lambda_i(\Sigma(E - \lambda_0 F))|, \quad i = 1, \dots, r. \quad (5)$$

Here we have $\sigma_r > 0$ because both X_1 and Y_1 have full column-rank. Note that the size of E and F in (5) is r -by- r , which is smaller than n -by- n as in (4). In the sequel we use the expression (5) to identify $\kappa_i(A, B, \lambda_0)$.

3 Hermitian definite pairs

3.1 Specifications

When (A, B) is a Hermitian definite pair, all the eigenvalues are always real and nondefective, and there exists a nonsingular matrix X such that [2]

$$X^H A X = \begin{bmatrix} \lambda_0 I_r & 0 \\ 0 & A_1 \end{bmatrix}, \quad X^H B X = I_n, \quad (6)$$

where A_1 is a diagonal matrix containing the eigenvalues not equal to λ_0 . Hence the diagonals of Σ in (5) are the r positive singular values of the matrix $X_1 X_1^H$, which are equal to the eigenvalues of the matrix $X_1^H X_1$. Since (A, B) is a Hermitian definite pair it is natural to require that the perturbation matrices preserve the property, so (5) becomes the “structured” condition numbers $\kappa_i(A, B, \lambda_0; \mathbb{S})$, expressed by

$$\kappa_i(A, B, \lambda_0; \mathbb{S}) \equiv \sup_{\substack{\|E\|_2 \leq 1, \|F\|_2 \leq \tau \\ E = E^H, F = F^H}} |\lambda_i(\Sigma(E - \lambda_0 F))|, \quad i = 1, \dots, r. \quad (7)$$

Denoting $D = \Sigma^{1/2} = \text{diag}(\sqrt{\sigma_1}, \dots, \sqrt{\sigma_r})$, we see that the eigenvalues of $\Sigma(E - \lambda_0 F)$ are equal to those of the Hermitian matrix $D(E - \lambda_0 F)D$.

We further observe that $E - \lambda_0 F$ can represent an arbitrary Hermitian matrix H with $\|H\|_2 \leq 1 + \tau|\lambda_0|$, which can be done by letting $E = H/\|H\|_2$ and $F = -\tau E|\lambda_0|/\lambda_0$. Conversely, it is easily seen that the class of Hermitian matrices H with $\|H\|_2 \leq 1 + \tau|\lambda_0|$ includes all the matrices expressed by $E - \lambda_0 F$. Together with the fact that the singular values of a Hermitian matrix are simply the absolute values of the eigenvalues, we have yet another characterization of condition numbers in the Hermitian definite case

$$\kappa_i(A, B, \lambda_0; \mathbb{S}) = (1 + \tau|\lambda_0|) \sup_{\substack{\|H\|_2 \leq 1 \\ H = H^H}} \sigma_i(DHD), \quad i = 1, \dots, r. \quad (8)$$

3.2 Identifying the condition numbers

Now we are ready to identify the condition numbers $\kappa_i(A, B, \lambda_0; \mathbb{S})$ using the expression (8).

Theorem 1 *In the Hermitian definite case, $\kappa_i(A, B, \lambda_0; \mathbb{S})$ as in (7),(8) is*

$$\kappa_i(A, B, \lambda_0; \mathbb{S}) = (1 + \tau|\lambda_0|) \min_{1 \leq j \leq i} \sqrt{\sigma_j \sigma_{i-j+1}}, \quad i = 1, \dots, r. \quad (9)$$

Note that $\sqrt{\sigma_j \sigma_{i-j+1}}$ is the geometric mean of σ_j and σ_{i-j+1} , the j th largest and smallest of $(\sigma_1, \sigma_2, \dots, \sigma_i)$, which is the set of the i largest singular values of $X_1^H X_1$.

Proof In view of (8), to prove the theorem it suffices to prove that for any Hermitian H such that $\|H\|_2 = 1$, $\sigma_i(DHD)$ is bounded above by $\min_j \sqrt{\sigma_j \sigma_{k-j+1}}$ for $i = 1, \dots, r$, and that this bound is attainable.

First, proving attainability is simply done by considering the case where H is zero except for its $i \times i$ leading principal submatrix, which is set to the antidiagonal matrix (which has 1 on the antidiagonals and 0 elsewhere). This choice of H makes the $i \times i$ leading principal submatrix of DHD also an anti-diagonal matrix, whose j th antidiagonal is $\sqrt{\sigma_j \sigma_{i-j+1}}$. Hence we have $\sigma_i(DHD) = \min_j \sqrt{\sigma_j \sigma_{i-j+1}}$.

Our remaining task is to prove that $\min_j \sqrt{\sigma_j \sigma_{i-j+1}}$ is an upper bound of $\sigma_i(DHD)$ for any Hermitian H with $\|H\|_2 \leq 1$. Using the max-min characterization of singular values [8, p. 68], we have

$$\sigma_i(DHD) = \max_{Q^H Q = I_i} \min_{\|v\|_2=1} \|DHDQv\|_2,$$

so it suffices to show that for any $Q \in \mathbb{C}^{r \times i}$ with orthonormal columns, there exists a unit vector v such that $\|DHDQv\|_2 \leq \min_j \sqrt{\sigma_j \sigma_{i-j+1}}$.

To prove this, let $j_0 = \text{argmin}_{j \leq (i+1)/2} \sqrt{\sigma_j \sigma_{i-j+1}}$. Since for any Q we have $\text{rank}(Q(1 : i - j_0, :)) \leq i - j_0$, there are at least j_0 linearly independent vectors in $\mathbb{C}^{i \times 1}$ that are orthogonal to the rows of Q . Therefore there must

exist $P \in \mathbb{C}^{i \times j_0}$ with orthonormal columns such that the first $i - j_0$ rows of the r -by- j_0 matrix QP are all zeros. For such P , we have

$$\|DQP\|_2 = \|\text{diag}(0, \dots, 0, \sqrt{\sigma_{i-j_0+1}}, \dots, \sqrt{\sigma_r})QP\|_2 \leq \sqrt{\sigma_{i-j_0+1}}.$$

Furthermore, since $\text{rank}(HDQP(1:j_0-1,:)) \leq j_0-1$, there must exist a unit vector $w \in \mathbb{C}^{j_0 \times 1}$ that is orthogonal to $HDQP(1:j_0-1,:)$, so that the first j_0-1 rows of $HDQPw$ are all zeros. We easily see that for such w we have $\|DHDQPw\|_2 \leq \sqrt{\sigma_{j_0}\sigma_{i-j_0+1}}$. Therefore we have shown that for any $Q \in \mathbb{C}^{k \times i}$ with orthonormal columns there exists a unit vector $v_0 = Pw$ such that

$$\min_{\|v\|_2=1} \|DHDQv\|_2 \leq \|DHDQv_0\|_2 \leq \sqrt{\sigma_{j_0}\sigma_{i-j_0+1}} = \min_j \sqrt{\sigma_i\sigma_{i-j+1}}.$$

□

Three remarks are in order.

- When $B \neq I_n$, σ_i for $i = 1, \dots, r$ generally take different values, so (9) shows that a multiple generalized eigenvalue has multiple condition numbers, which is our main result. Note that the ratio among the condition numbers is bounded by $\kappa_1(A, B, \lambda_0; \mathbb{S})/\kappa_r(A, B, \lambda_0; \mathbb{S}) \leq \sigma_1/\sigma_r$. Now since $\sigma_{\min}(B^{-1}) \leq \sigma_r \leq \sigma_1 \leq \sigma_{\max}(B^{-1})$, we have $\sigma_1/\sigma_r \leq \sigma_{\max}(B)/\sigma_{\min}(B) = \kappa_2(B)$, the standard 2-norm condition number of B . It follows that if B is well-conditioned then a multiple eigenvalue of a Hermitian definite pair must have similar condition numbers.
- For standard Hermitian eigenvalue problems ($B = I_n$), we have $d_i \equiv 1$ and $\tau = 0$, so (9) reduces to $\kappa_i = 1$ for all i , the well-known result that a multiple eigenvalue of a Hermitian matrix has a uniform condition number 1. When one allows for perturbation in $B = I_n$, the condition numbers are $1 + \tau|\lambda_0|$ regardless of the multiplicity. The second term suggests that larger changes occur in larger eigenvalues. This observation can be summarized as follows: for perturbation in A , all the eigenvalues have the same sensitivity in the absolute sense, while for perturbation in B , all the eigenvalues have the same sensitivity in the relative sense.
- The above arguments show that the difference among condition numbers of a multiple eigenvalue is due to the difference among the r singular values of $X_1 Y_1^H$, the outer product of the left and right eigenvectors corresponding to λ_0 . $\sigma_i(X_1 Y_1^H)$ are all 1 in the standard Hermitian case because $X_1 = Y_1$ and it is an orthogonal matrix. In the standard non-Hermitian case $X_1 \neq Y_1$ and neither is orthogonal, so $\sigma_i(X_1 Y_1^H)$ take r different values. In the generalized Hermitian case we have $X_1 = Y_1$ but X_1 is not orthogonal, so $\sigma_i(X_1 X_1^H)$ again take r different values. Note that one uses the B -based inner product this difference disappears because X_1 is B -orthogonal, recall the remark in the introduction.

4 Non-Hermitian pairs

Here we consider the case where (A, B) is a general non-Hermitian pair. In view of (5), our task is to bound $|\lambda_i(X\Sigma)|$ for an arbitrary square matrix X such that $\|X\|_2 \leq 1$. This is in fact the exact same problem addressed in [13, Thm.3.1]. Hence the analysis there can be directly applied to yield the following result.

Theorem 2 *For a non-Hermitian pair (A, B) that satisfies (2), let $\sigma_1 \geq \sigma_2 \geq \dots \geq \sigma_r > 0$ be the positive singular values of the matrix $X_1 Y_1^H$. Then, $\kappa_i(A, B, \lambda_0)$ in (5) can be expressed as*

$$\kappa_i(A, B, \lambda_0) = (1 + \tau|\lambda_0|) \left(\prod_{j=1}^i \sigma_j \right)^{1/i}, \quad i = 1, \dots, r. \quad (10)$$

4.1 Structured perturbation

It is instructive to revisit the Hermitian definite case, but now allowing for non-Hermitian perturbations, that is, E, F are general matrices whose norms are bounded by 1. In this case, the condition numbers $\kappa_i(A, B, \lambda_0)$ have the characterization (5) (instead of (8)), so they have the expression (10), the same as that for the non-Hermitian pair.

As might be expected, the condition number under Hermitian perturbation (9) is always no larger than that under a non-Hermitian perturbation (10):

$$\begin{aligned} \frac{\kappa_i(A, B, \lambda_0; \mathbb{S})}{1 + \tau|\lambda_0|} &= \left(\min_{1 \leq j \leq i} (\sigma_j \sigma_{i-j+1})^i \right)^{1/2i} \leq \left(\prod_{j=1}^i (\sigma_j \sigma_{i-j+1}) \right)^{1/2i} \\ &= \left(\prod_{j=1}^i \sigma_j^2 \right)^{1/2i} = \left(\prod_{j=1}^i \sigma_j \right)^{1/i} = \frac{\kappa_i(A, B, \lambda_0)}{1 + \tau|\lambda_0|}. \end{aligned}$$

The above arguments imply that if the singular values of $X_1 Y_1^H$ are the same, then under a general non-Hermitian perturbation the condition numbers $\kappa_i(A, B, \lambda_0)$ are all the same¹, regardless of whether (A, B) is Hermitian definite or non-Hermitian. Therefore, the structure of the perturbation matrices plays an important role in the perturbation sensitivity of a multiple generalized eigenvalue. We note that the standard Hermitian case with $B \equiv I$ is an exception, in which the condition numbers are always all 1 whether or not the perturbation matrices are Hermitian.

This point of view, to focus on the effect of the structure of the perturbation, was investigated extensively in [4], in which (Theorem 4.5) it is shown that (among other structures they consider) the Hermitian structure of the

¹ In fact the entire first order perturbation expansions become the same.

perturbation matrices does not have any effect on the Hölder condition number.

At first sight this seems to contradict our results, which show that the Hermitian structure of the perturbation matrices does affect the condition numbers of the multiple eigenvalue λ_0 . The explanation is that [4] treats only the Hölder condition number, which is equivalent to $\kappa_1(A, B, \lambda_0)$ in the non-defective case. Here we are identifying individual condition numbers of each of the r eigenvalues. In fact, we can see that for $i = 1$, κ_i in (9) and (10) are the same, both equal to $(1 + \tau|\lambda_0|)\sigma_1$. We can easily see that they are equal also for $i = 2$. The difference between (9) and (10) starts to take effect only for $i \geq 3$, so λ_0 's multiplicity r must be at least 3. In particular, for a simple eigenvalue the Hermitian structure of the perturbation has no effect on the condition number, which is a trivial consequence of the results in [4].

4.2 Examples

Here we present two simple examples to illustrate the above results and observations.

Example 1 For the Hermitian definite pair $A = \begin{bmatrix} 2000 & 0 \\ 0 & 2 \end{bmatrix}$, $B = \begin{bmatrix} 1000 & 0 \\ 0 & 1 \end{bmatrix}$ presented in [10, p.300], we have $\kappa_1(A, B, \lambda_0; \mathbb{S}) = \kappa_1(A, B, \lambda_0) = 3$ and $\kappa_2(A, B, \lambda_0; \mathbb{S}) = \kappa_2(A, B, \lambda_0) = 3/\sqrt{1000}$, which explains why the multiple eigenvalue $\lambda_0 = 2$ has different sensitivities. Note that in this case the structure of the perturbation has no effect on the condition numbers, because the multiplicity of λ_0 is $r < 3$.

Example 2 We consider a 4-by-4 Hermitian definite pair (A, B) expressed by

$$A = W^H \Lambda W, \quad B = W^H W,$$

where $\Lambda = \text{diag}(1, 1, 1, 2)$ and $W = \text{diag}(1, 2, 100, 1)$, so the eigenvalues of (A, B) are 1, 1, 1, 2. Since X that diagonalizes A, B (as in (6)) is $X = W^{-1} = \text{diag}(1, 0.5, 0.01, 1)$ and X_1 is its first three columns, the singular values of $X_1 X_1^H$ are $\sigma_1 = 1^2, \sigma_2 = 0.5^2, \sigma_3 = 0.01^2$ (where in this example we let $\tau = 1$), hence by (9) it follows that $\kappa_1(A, B, 1; \mathbb{S}) = 2, \kappa_2(A, B, 1; \mathbb{S}) = 1$ and $\kappa_3(A, B, 1; \mathbb{S}) = 0.02$. Using MATLAB version 7.10 we generated 10^6 sets of random Hermitian perturbation matrices E and F such that $\|E\|_2, \|F\|_2 \leq 1$, and examined the behavior of the three eigenvalues of the pair $(A + \epsilon E, B + \epsilon F)$ that are closest to $\lambda_0 = 1$, where we let $\epsilon = 10^{-5}$. Specifically, denoting by $\hat{\lambda}_i$ for $i = 1, 2, 3$ the three eigenvalues of $(A + \epsilon E, B + \epsilon F)$ that are closest to 1 such that $|\hat{\lambda}_1 - 1| \geq |\hat{\lambda}_2 - 1| \geq |\hat{\lambda}_3 - 1|$, we examine how large $|\hat{\lambda}_i - 1|/\epsilon$ can be for $i = 1, 2, 3$.

We also experimented with non-Hermitian perturbations, in which case we let E, F be arbitrary non-Hermitian matrices with $\|E\|_2, \|F\|_2 \leq 1$. In this case the condition numbers (10) are $\kappa_1(A, B, 1) = 2, \kappa_2(A, B, 1) = 2(1 \cdot$

$0.5^2)^{1/2} = 1$ and $\kappa_3(A, B, 1) = 2(1 \cdot 0.5^2 \cdot 0.01^2)^{1/3} \simeq 0.058$, in which we confirm that the first two are the same as in the above Hermitian case.

Lastly, in order to see how the Hermitian property of the matrices plays a role in the eigenvalue perturbation behaviors, we also tested with a non-Hermitian pair (A, B) that has the same eigenvalues and σ_i (of $X_1 Y_1^H$) as the above Hermitian pair. We formed such a pair (A, B) by defining $A = Y^{-H} \Lambda X^{-1}$ and $B = Y^{-H} X^{-1}$, where $\Lambda = \text{diag}(1, 1, 1, 2)$, Y_1^H (the first 3 rows of Y) is set to $Z \Sigma V^H$ and X_1 (the first 3 columns of X) is set to $U Z^{-1}$, where U and V are randomly generated matrices with orthonormal columns, $\Sigma = \text{diag}(\sigma_1, \sigma_2, \sigma_3) = (1^2, 0.5^2, 0.01^2)$ and Z is an arbitrary nonsingular matrix². Elements of the last row of Y and the last column of X were taken as random numbers. Since we have $X_1 Y_1^H = U \Sigma V^H$, we have $\kappa_1(A, B, 1) = 2$, $\kappa_2(A, B, 1) = 1$ and $\kappa_3(A, B, 1) = 0.058$, the same condition numbers as the above second case with non-Hermitian perturbation, as was intended. The perturbations E and F are taken as arbitrary non-Hermitian matrices.

In summary we tested under three different situations, all of which have the same $\sigma_i(X_1 Y_1^H)$: (i) Both (A, B) and (E, F) are Hermitian (shown as “Her + Her” in Table 2), (ii) (A, B) is Hermitian but (E, F) is non-Hermitian (“Her + NonHer”), and (iii) Both (A, B) and (E, F) are non-Hermitian (“NonHer + NonHer”).

The results are summarized in Table 2 below, which shows the average and maximum (shown as avg. and max respectively) values of $\Delta\lambda_i/\epsilon = |\hat{\lambda}_i - 1|/\epsilon$ among the 10^6 runs with randomly generated E and F , along with the condition numbers $\kappa_i(A, B, \lambda_0)$ (which are first order upper bounds for $\Delta\lambda_i/\epsilon$) for $i = 1, 2, 3$.

Table 2 Average and maximum perturbation $\Delta\lambda_i/\epsilon$ of 10^6 runs for $i = 1, 2, 3$.

i	Her + Her			Her + NonHer			NonHer + NonHer		
	avg.	max	κ_i	avg.	max	κ_i	avg.	max	κ_i
1	0.579	1.98	2.0	0.41	1.86	2.0	0.42	1.90	2.0
2	0.141	0.84	1.0	0.136	0.76	1.0	0.137	0.76	1.0
3	0.00018	0.012	0.02	0.00021	0.027	0.058	0.00021	0.027	0.058

We make the following observations.

- We confirm that κ_i is an upper bound of $\max \Delta\lambda_i/\epsilon$ for all i in all three cases (which is necessarily true in the limit $\epsilon \rightarrow 0$). Interestingly, for $i = 1$ the bound κ_i is nearly attained while for $i = 2, 3$, $\max \Delta\lambda_i/\epsilon$ is noticeably smaller than κ_i , which suggests that for larger i it becomes more and more rare that the largest-possible perturbation is attained.
- Reflecting the fact that κ_i are the same for all the three cases for $i = 1$ and 2, we can see that $\max \Delta\lambda_i/\epsilon$ are similar in all three cases, so two eigenvalues have similar maximum sensitivities regardless of whether A, B, E, F

² Note that the choice of Z does not affect the condition numbers $\kappa_i(A, B, 1)$.

are Hermitian or not. On the contrary, $\max \Delta\lambda_i/\epsilon$ for $i = 3$ show the somewhat different sensitivities of the third eigenvalue depending on the structure of E, F .

- The behavior of the multiple eigenvalue is remarkably similar for the latter two cases, not only in terms of $\max \Delta\lambda_i/\epsilon$ but also $\text{avg.} \Delta\lambda_i/\epsilon$. This reflects the fact that the first order expansions of λ_0 are the same for the two cases, so that the local behavior of an eigenvalue is determined solely by the singular values of $X_1 Y_1^H$, and does not depend on the structure of the matrices A and B .
- Comparing $\text{avg.} \Delta\lambda_i/\epsilon$ with $\max \Delta\lambda_i/\epsilon$, we see that the former is much smaller than the latter for larger i . For $i = 1$ the difference seems less significant.

A precise explanation for the last two observations, which necessarily involves statistical analysis, is an open problem: our discussions deal only with the maximum attainable perturbation $\max \Delta\lambda_i/\epsilon$, not with $\text{avg.} \Delta\lambda_i/\epsilon$.

4.3 Defective and infinite cases

So far we have treated only the case where λ_0 is a finite and nondefective multiple eigenvalue. Here we briefly consider the cases where λ_0 is infinite and/or defective.

The case $\lambda_0 = \infty$ can be treated as in [1,4] simply by considering the multiple zero eigenvalue of the pair (B, A) , for which the exact same discussion as above is valid.

When λ_0 is defective, Lidskii's perturbation theory [1,4] shows that the leading term in λ_0 's perturbation expansion is not linear in ϵ . Specifically, if λ_0 is an eigenvalue of (A, B) of multiplicity $n_1 r$ belonging to a Jordan block of dimension n_1 repeated r times, then there are $n_1 r$ eigenvalues of $(A + \epsilon E, B + \epsilon F)$ admitting the expansion

$$\hat{\lambda}_{i,\ell} = \lambda_0 + (\lambda_i(Y_1^H(E - \lambda_0 F)X_1))^{1/n_1} \epsilon^{1/n_1} + o(\epsilon^{1/n_1}) \quad (11)$$

for $i = 1, 2, \dots, r$ and $\ell = 1, 2, \dots, n_1$. Here $Y_1^H \in \mathbb{C}^{r \times n}$ and $X_1 \in \mathbb{C}^{n \times r}$ represent the linearly independent left and right eigenvectors of (A, B) corresponding to λ_0 , and the value $(\lambda_i(Y_1^H(E - \lambda_0 F)X_1))^{1/n_1}$ takes all the n_1 distinct n_1 th roots.

We observe in (11) that although the leading exponent is different from that in (3), the sensitivities of the multiple eigenvalue are still governed by $|\lambda_i(Y_1^H(E - \lambda_0 F)X_1)|$ for $i = 1, \dots, r$, for which we gave a bound in the above discussions. Hence all our previous results carry over to this case, and the condition numbers of λ_0 with the exponent $1/n_1$, which we define by the theoretical bounds for $\sup_{\|E\|_2 \leq 1, \|F\|_2 \leq \tau} |\lambda_i(Y_1^H(E - \lambda_0 F)X_1)|^{1/n_1}$, are

$$\kappa_{i,n_1}(A, B, \lambda_0) = \left((1 + \tau|\lambda_0|) \left(\prod_{j=1}^i \sigma_j \right)^{1/i} \right)^{1/n_1}, \quad i = 1, \dots, r.$$

By (11), we must have $|\hat{\lambda}_{i,\ell} - \lambda_0|/\epsilon^{1/n_1} \leq \kappa_{i,n_1}(A, B, \lambda_0)$ for $i = 1, \dots, r$ in the limit $\epsilon \rightarrow 0$ for any E and F . Note that $\kappa_{i,n_1}(A, B, \lambda_0)$ does not depend explicitly on ℓ . We observe that in the defective case $n_1 \geq 2$, the exponent $1/n_1$ makes the difference among the condition numbers less significant than in the nondefective case. See the example below for an illustration.

4.3.1 Example

To examine the behavior of a defective multiple eigenvalue, we generate a 7-by-7 pair (A, B) defined by

$$A = Y^{-H} \begin{bmatrix} J & & & & & & \\ & J & & & & & \\ & & J & & & & \\ & & & 2 & & & \\ & & & & & & \\ & & & & & & \\ & & & & & & \end{bmatrix} X^{-1}, \quad \text{and} \quad B = Y^{-H} X^{-1}, \quad (12)$$

where $J = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$ is a 2-by-2 Jordan block. (A, B) has a multiple eigenvalue $\lambda_0 = 1$ of multiplicity six and a simple eigenvalue 2. $Y_1^H \equiv [Y(:, 2) \ Y(:, 4) \ Y(:, 6)]^H = Z\Sigma V^H$ and $X_1 \equiv [X(:, 1) \ X(:, 3) \ X(:, 5)] = UZ^{-1}$ are the left and right eigenvectors corresponding to λ_0 , where U and V are random matrices with orthonormal columns and Z is an arbitrary nonsingular matrix. The other rows of Y^H and columns of X do not affect the condition numbers of λ_0 , so we let them take random values. We let $\Sigma = \text{diag}(1^2, 0.5^2, 0.01^2)$, so that $\sigma_i(X_1 Y_1^H)$ take the same values as in the non-Hermitian case of the second example in section 4.2.

Recall from (11) that perturbation in (A, B) generally makes λ_0 split into $n_1 r$ perturbed eigenvalues $\hat{\lambda}_{i,\ell}$ for $i = 1, \dots, r$ and $\ell = 1, \dots, n_1$. (11) also shows that for a fixed i , $|\hat{\lambda}_{i,\ell} - \lambda_0|$ must be nearly equal for all ℓ up to $o(\epsilon^{1/n_1})$. For the matrix pair (12) we have $r = 3$ and $n_1 = 2$, so we separate the six eigenvalues $\hat{\lambda}_{i,\ell}$ into three groups according to the value of i , so that the two eigenvalues of the i th group have perturbation sensitivity governed by $|\lambda_i(Y_1^H(E - \lambda_0 F)X_1)|^{1/n_1}$.

With $\tau = 1$, the condition numbers $\kappa_{i,2}(A, B, 1)$ for the i th group for $i = 1, 2, 3$ are $\kappa_{1,2}(A, B, 1) = (2 \cdot 1)^{1/2} = \sqrt{2}$, $\kappa_{2,2}(A, B, 1) = (2 \cdot (1 \cdot 0.5^2)^{1/2})^{1/2} = 1$ and $\kappa_{3,2}(A, B, 1) = (2 \cdot (1 \cdot 0.5^2 \cdot 0.01^2)^{1/3})^{1/2} \simeq 0.24$. Comparing these with $\kappa_i(A, B, 1)$ in the example in section 4.2 we see that although $\sigma_i(X_1 Y_1^H)$ take the same values, the relative difference among the condition numbers is smaller here, due to the exponent 1/2.

Recalling that we must have $|\hat{\lambda}_{i,\ell} - 1|/\epsilon^{1/2} \leq \kappa_{i,2}(A, B, 1)$ for small ϵ , here we examine how large $|\hat{\lambda}_{i,\ell} - 1|/\epsilon^{1/2}$ becomes for $i = 1, 2, 3$. To do this, of the six eigenvalues of $(A + \epsilon E, B + \epsilon F)$ close to λ_0 , we check the perturbation of the most perturbed, third perturbed, and the fifth perturbed ones.

In the experiment we let E, F be random non-Hermitian matrices with $\|E\|_2, \|F\|_2 \leq 1$, let $\epsilon = 10^{-6}$ and tested with 10^6 pairs. In table 3 we report the average and maximum values of $|\hat{\lambda}_{i,\ell} - 1|/\epsilon^{1/2}$ for $i = 1, 2, 3$.

Table 3 Defective matrix pair (12) with three 2×2 Jordan blocks, average and maximum perturbation $|\hat{\lambda}_{i,\ell} - 1|/\epsilon^{1/2}$ of 10^6 runs for $i = 1, 2, 3$.

i	avg.	max	$\kappa_{i,2}$
1	0.511	1.21	1.41
2	0.282	0.733	1
3	0.0089	0.138	0.24

Similarly to the experiments in section 4.2 for nondefective multiple eigenvalues, we see that a defective multiple eigenvalue also exhibits different sensitivities under perturbation. We also tested with Hermitian perturbations $E = E^H$ and $F = F^H$, and obtained nearly the same results as in Table 2. This suggests that the structure of the perturbation does not play a role here.

In all our experiments we had $|\hat{\lambda}_{i,1} - \hat{\lambda}_{i,2}|/\epsilon^{1/2} < 0.04$ for $i = 1, 2, 3$, which matches the theoretical result indicated by (11) that for a given i , $|\hat{\lambda}_{i,\ell} - 1|$ are equal up to $o(\epsilon^{1/n_1})$ for all ℓ .

Finally, a comparison between Table 3 and the third case of Table 2 suggests that the relative difference among the multiple eigenvalues is smaller in the defective case, reflecting the last remark before this example.

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